Atmospheric Refraction Correction for Ka-Band Blind Pointing on the DSS-13 Beam Waveguide Antenna

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An analysis of the atmospheric refraction corrections at the DSS-13 34-m diameter beam waveguide antenna for the period covering July through December 1990 is presented. The current DSN atmospheric refraction model and its sensitivity with respect to sensor accuracy are reviewed. Refraction corrections based on actual atmospheric parameters are compared with the DSS-13 station default corrections for the six-month period. Average blind-pointing improvement during the worst month would have amounted to 5 mdeg at 10 deg elevation using actual surface weather values. This would have resulted in an average gain improvement of 1.1 dB.

I. Introduction

The bending of radio waves as they pass obliquely through the atmosphere can produce large pointing errors. Currently in the DSN, a refraction model (referred to here as the Lanyi model[1] is used to compute a correction which reduces antenna beam-pointing errors in elevation. The inputs to the refraction model are predicted elevation angle, surface atmospheric pressure, surface temperature, and surface relative humidity. The use of actual weather parameter inputs from antenna station instrumentation, instead of from default values, will significantly improve blind-pointing accuracy. This article investigates the magnitude of the pointing improvement by analyzing real atmospheric conditions at the DSS-13 beam waveguide (BWG) antenna.

During the phase 1 testing period [1] at DSS 13, gain and pointing calibrations were conducted from June 1990 through January 1991. Throughout this period the Lanyi refraction model was used to compute and apply refraction corrections based on station default weather parameters coded in the Antenna Controller Subassembly (ACS). Station weather instrumentation readings, not interfaced with the antenna-pointing system at the time, were also logged at ten-minute intervals. These atmospheric readings allow analysis and comparison of actual weather-based refraction corrections with the fixed-parameter corrections during the experiment period.

It was anticipated that actual beam-pointing error measurements made on stellar radio sources during the phase 1

[1] G. Lanyi, "Atmospheric Refraction Corrections to Antenna Pointing at 1 Millidegree Accuracy," JPL Interoffice Memorandum 335.3-89-026, Jet Propulsion Laboratory, Pasadena, California, March 24, 1989.

testing would enable assessment of the reduction of actual elevation pointing errors. Unfortunately, only a limited number of measurements were made at the lower elevation angles, and they appeared to be of only marginal quality. Due to the nonrepeatable nature and poor quality of these pointing measurements, they were deemed unreliable for the purpose of analysis. In this article, estimated improvement in the refraction pointing error correction at DSS 13 is based strictly on the deviation of the logged meteorological parameters (pressure, temperature, and relative humidity) from the default DSS-13 weather parameters.

The data analysis to be presented will span the real-time weather input measurement period between July 1 and December 31, 1990. The data acquisition and reduction techniques are described. The Lanyi refraction model, along with its sensitivity to input weather parameters, is reviewed. It is shown that the magnitude of the refraction pointing error correction based on actual atmospheric parameters deviates significantly from the default, on the average, as the elevation tracking angle decreases. The Ka-band gain loss corresponding to deviations in the corrections emphasizes the need for accurate, real-time weather inputs to the DSN refraction correction algorithm.

II. Refraction Correction in the DSN

A. Background

Until 1990, the DSN used the Berman–Rockwell refraction model defined in [2,3]. In 1990, the Lanyi model was implemented in the DSN, as well as at the DSS-13 34-m BWG antenna. A detailed comparison of the models can be obtained through the references. The main motivation for implementing the Lanyi model was its estimated improvement in accuracy, especially at the low-elevation angles. The estimated Lanyi model accuracy is stated to be better than 0.5 mdeg at elevation angles greater than 6 deg, assuming that accurate and current measurements of the atmosphere are provided to the antenna controller. In terms of the current DSN Media Calibration Subsystem (DMD) weather instrumentation specifications, this could produce an error of 1.5 to 4.0 mdeg at 6 deg elevation for average and extreme DSN water vapor content, respectively. Such pointing errors may seem small but are significant when contemplating error budgets for Ka-band beamwidths (17 mdeg for 34-m antennas and 9 mdeg for 70-m antennas).

B. The Lanyi Refraction Model

The Lanyi refraction model has the basic functional form of

$$\Delta EL = f(P, T, RH, EL) \tag{1}$$

where

ΔEL = change in elevation pointing

P = surface pressure

T = surface temperature

RH = surface relative humidity

EL = predicted elevation angle

The DSN default surface weather parameters, which were used at DSS 13 are

P = 901.09 mbar

T = 22.07 deg C

RH = 31.57 percent

Figure 1 shows the magnitude of the refraction corrections at DSS 13 as a function of elevation angle, using the default weather parameters.

III. DSS-13 Surface Atmosphere Measurements

A. Weather Instrumentation and Measurement Analysis

Daily records of surface atmospheric conditions at DSS 13 were collected from July through December 1990. These time-tagged measurements provide the basis for computation of actual refraction corrections, which were used for comparison with the default corrections. It is thus necessary to try to assess the quality of the measurements.

Two sensors for each weather parameter were operational during the period of interest, and their observations were recorded every 10 min by the station weather data acquisition computer. The accuracy specifications of the instruments are stated to be

Pressure: 800 to 1100 mbar, ±0.3 mbar

Temperature: −50 to +80 deg C, ±0.1 deg C

Relative humidity: 0 to 80 percent, ±2 percent, and
80 to 100 percent, ±3 percent

The differences between the two sensors for each measurement (25,329 data points) were computed. The average difference between the two sensors for all days was computed to be

Pressure: 0.0493 mbar ($\sigma = 0.0791$ mbar)

Temperature: 0.0710 deg C ($\sigma = 0.1428$ deg C)

Relative humidity: 3.9 percent ($\sigma = 3.7$ percent)

Both the pressure and temperature sensor pairs agreed extremely well during this period, while at least one relative humidity probe appeared to be biased. The differences also display large variations. To illustrate the variability in the humidity sensors, Fig. 2 shows the average daily difference between the humidity observations for days 267 through 321. The readings from sensor 2 are always larger than those registered by sensor 1. The true relative humidity value may lie between the sensor readings, or one or both of the sensors may be biased high or low. These discrepancies in humidity can map into significant differences in refraction correction, especially at low elevation angles. To minimize the impact on the refraction correction analysis, the atmospheric measurements were filtered in the following manner: Points were eliminated when the difference between the two measurements from each of the sensors was greater than twice the stated DSS-13 accuracy specification. Approximately twenty percent of the data points were removed in this manner.

B. Sensor Error Propagation

As noted, uncertainties in all three surface weather measurements will propagate into errors in the computed refraction corrections. To quantify the correction degradation, the sum of the squares of the partial derivatives of the refraction model with respect to each input parameter were computed.

A first-order approximation to the Lanyi model, which is adequate for sensitivity analysis, is given by

$$\Delta EL = \frac{\chi_0 - Z_{tot}/\left(R\sin^2(EL)\right)}{\tan(EL)} \qquad (2)$$

where

$\chi_0 = \chi_{dry} + \chi_{wet} =$ total surface refractivity

$Z_{tot} = Z_{dry} + Z_{wet} =$ total zenith path delay

$R =$ Earth radius

$EL =$ the uncorrected elevation angle

The dry and wet surface refractivities and dry and wet zenith path delays can be determined from surface measurements of pressure, temperature, and relative humidity. The DSS-13 weather instrumentation specifications were then input as uncertainties and yielded an error of 0.71 mdeg in the computed refraction correction at 10 deg elevation. Thus, the sensor error propagation would not be a major problem in this current study if all the sensors were within their accuracy limits.

Figure 3 shows the DSS-13 rss refraction correction error at 10 deg elevation due to relative humidity uncertainty, using the default weather parameters and the given pressure and temperature sensor specifications. It is seen that when the sensor error increases above 3 percent, refraction error correction on the millidegree level is unachievable.

IV. Refraction Correction Analysis

A. Computed Refraction Corrections

Refraction corrections were computed at 1-hr intervals for the atmospheric measurement set spanning the six months (3446 points). In order to examine the variability of the computed corrections over this period, the extreme ranges of the sensor readings are considered. By setting two of the three input variables (pressure, temperature, and relative humidity) to the DSS-13 default values and entering the extreme points listed below into the refraction model, the correction ranges listed in Table 1, in millidegrees, are computed.

As seen in that table, the change in refraction correction due to relative humidity is about 17 times greater than that due to pressure and about 3 times greater than that due to temperature.

B. Effect on Gain

The absolute differences between the default refraction corrections and those corresponding to actual weather parameters were computed. The resultant values are assumed to be improvements in the beam-pointing accuracy for blind pointing if the real-time surface weather observations were used in the refraction correction for the six-month period. For all the hour-interval atmospheric measurements, the absolute difference is computed at elevation increments of 5 deg. Figure 4 illustrates the differences for the month of October 1990, which had the highest average refraction difference from the default refraction values.

Note that for this particular month, very few actual refraction corrections equaled the default corrections (absolute difference = 0). Thus, rarely would good blind pointing be achieved, and the average pointing errors at low elevation angles would be rather large (4.8 millidegrees). Expected beam-pointing improvement (using real weather inputs) increases significantly as the elevation angle is decreased.

To summarize the whole six-month period, statistics were computed for the entire data set at 5-deg increments. Figure 5 shows the means and standard deviations of the absolute differences. At 10 deg elevation, the refraction pointing error should, on the average, be reduced by 4 mdeg, with a 2.4-mdeg 1-σ variation. The expected DSS-13 Ka-band gain degradation corresponding to the average differences is shown in Fig. 6. X-band gain loss would be less than 0.1 dB. The large magnitude of the average gain loss at the lower elevations stresses the need for accurate, real-time weather inputs for refraction correction during Ka-band tracking operations.

Figure 7 shows the means of the absolute correction differences for the months of August and October, when the smallest and largest average differences were observed, respectively. Figure 8 illustrates the corresponding Ka-band gain loss. The plots indicate that on the average, the DSS-13 default weather parameters matched the actual atmospheric conditions best in August and worst in October.

V. Conclusions

An analysis of the atmospheric refraction correction at the DSS-13 BWG antenna for the period covering July through December 1990 has been presented. The Lanyi refraction model and its sensitivity with respect to sensor error were reviewed. It was shown that the present specifications on the DSS-13 weather instrumentation are sufficient to provide submillidegree refraction correction, however, performance will sharply degrade when the relative humidity sensors fail to meet their specified accuracy.

Refraction corrections based on actual atmospheric parameters from the six-month period were computed and compared with the DSS-13 station default corrections. The average worst-month differences between the corrections was 5 mdeg at 10 deg elevation (Fig. 7). The corresponding average Ka-band gain loss expected using the DSS-13 default weather parameters during this period was thus 1.1 dB at that elevation (Fig. 8). The X-band gain loss would be approximately 0.1 dB. This significant gain loss mandates the need for accurate, real-time weather-parameter-based refraction correction for future Ka-band tracking operations.

Acknowledgment

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References

[1] S. D. Slobin, T. Y. Otoshi, L. S. Alvarez, M. J. Britcliffe, S. R. Stewart, and M. M. Franco, "Efficiency Calibration of the DSS 13 34-Meter Beam Waveguide Antenna at 8.45 and 32 GHz," *TDA Progress Report 42-106*, vol. April–June 1991, Jet Propulsion Laboratory, Pasadena, California, pp. 283–297, August 15, 1991.

[2] A. L. Berman and S. T. Rockwell, *New Optical and Radio Frequency Angular Tropospheric Refraction Models for Deep Space Applications*, Technical Report 32-1601, Jet Propulsion Laboratory, Pasadena, California, November 1, 1975.

[3] A. L. Berman, "Modification of the DSN Radio Frequency Angular Tropospheric Refraction Model," *DSN Progress Report 42-38*, vol. January–February 1977, Jet Propulsion Laboratory, Pasadena, California, pp. 184–186, April 15, 1977.

Table 1. Effect of measured weather extremes on calculated refraction correction.

Parameter	Refraction correction, mdeg		
	10-deg elevation	20-deg elevation	30-deg elevation
Pressure, 883 to 907 mbar	83.6–85.6	41.7–42.7	26.5–27.1
Temperature, −9.7 to 37.7 deg C	84.3–95.1	42.1–47.4	26.7–30.1
Relative humidity, 4 to 99 percent	75.2–109.7	37.6–54.6	23.9–34.6

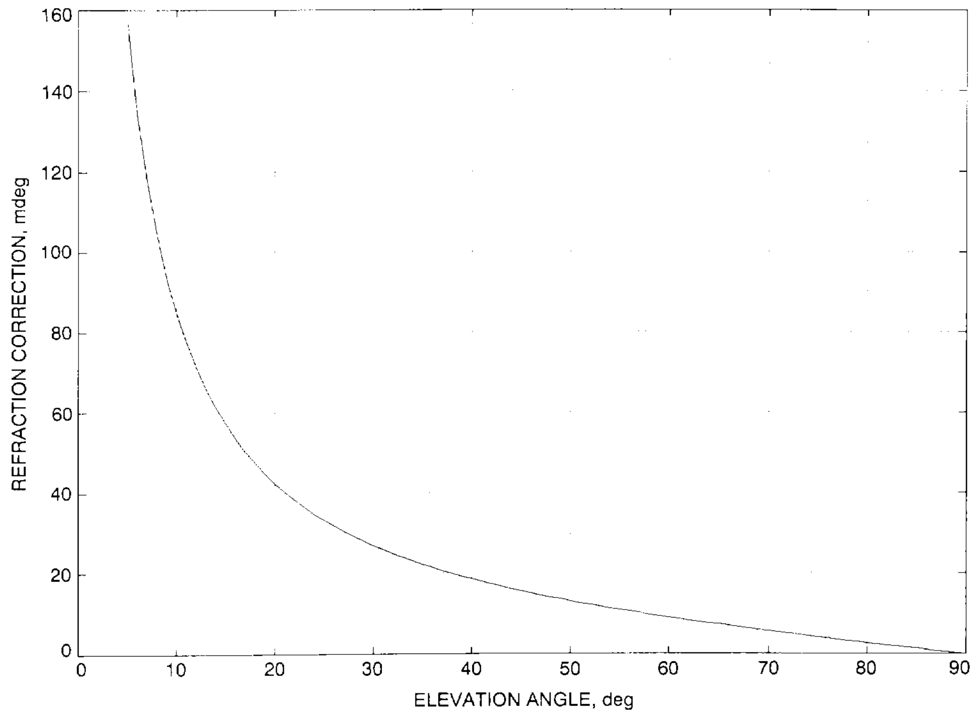

Fig. 1. Lanyi angular refraction correction model for DSS-13 default atmospheric parameters.

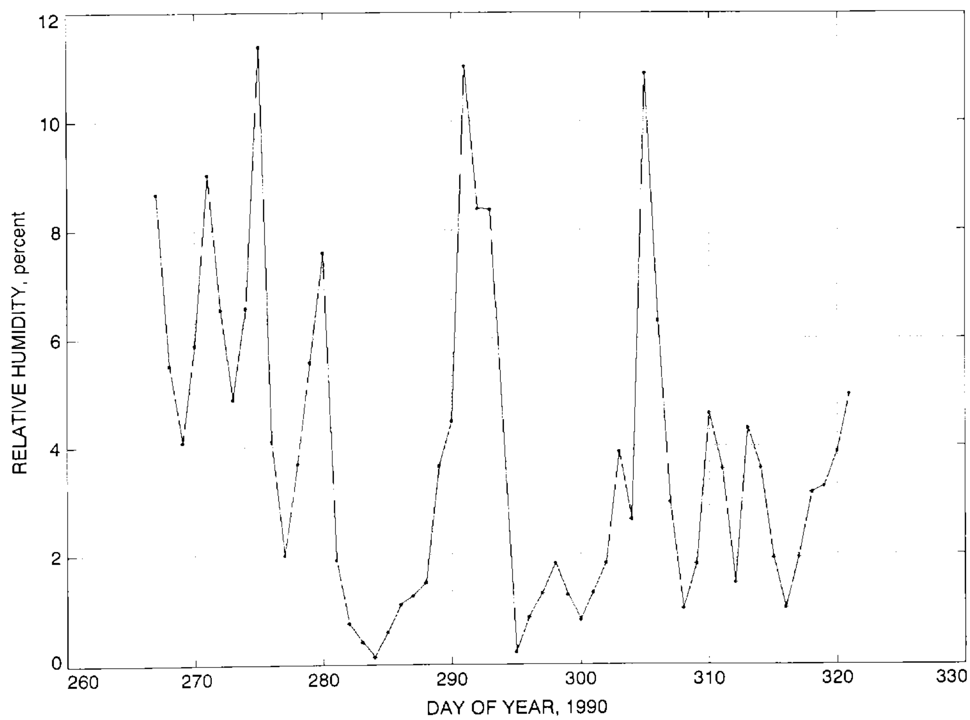

Fig. 2. Daily average difference between relative humidity probe readings.

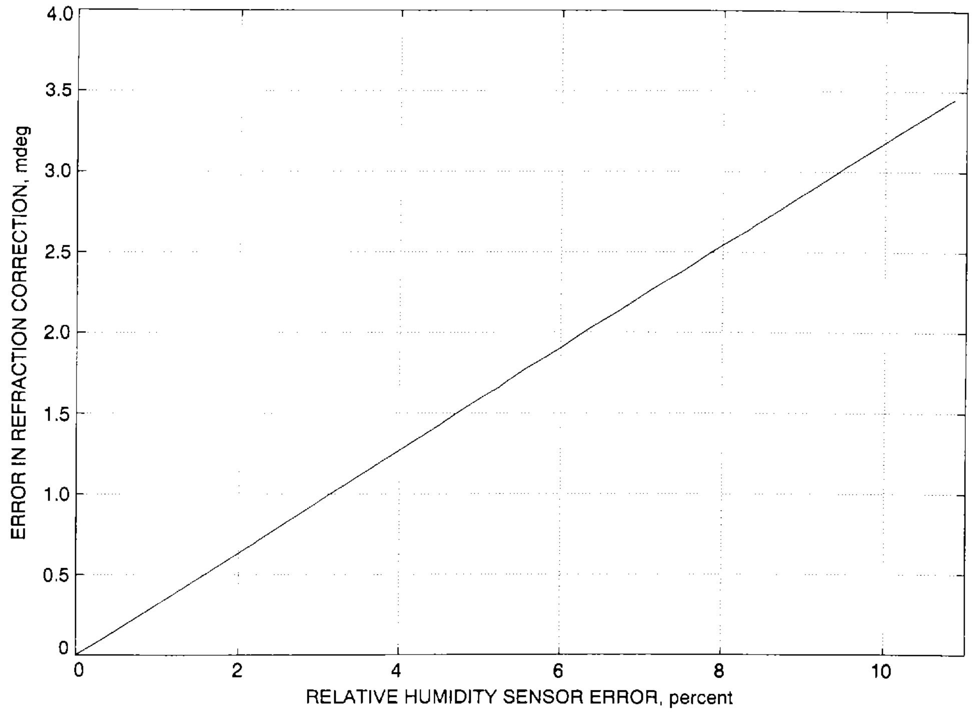

Fig. 3. Error in computed correction at 10 deg elevation, due to relative humidity instrument error, using default parameters.

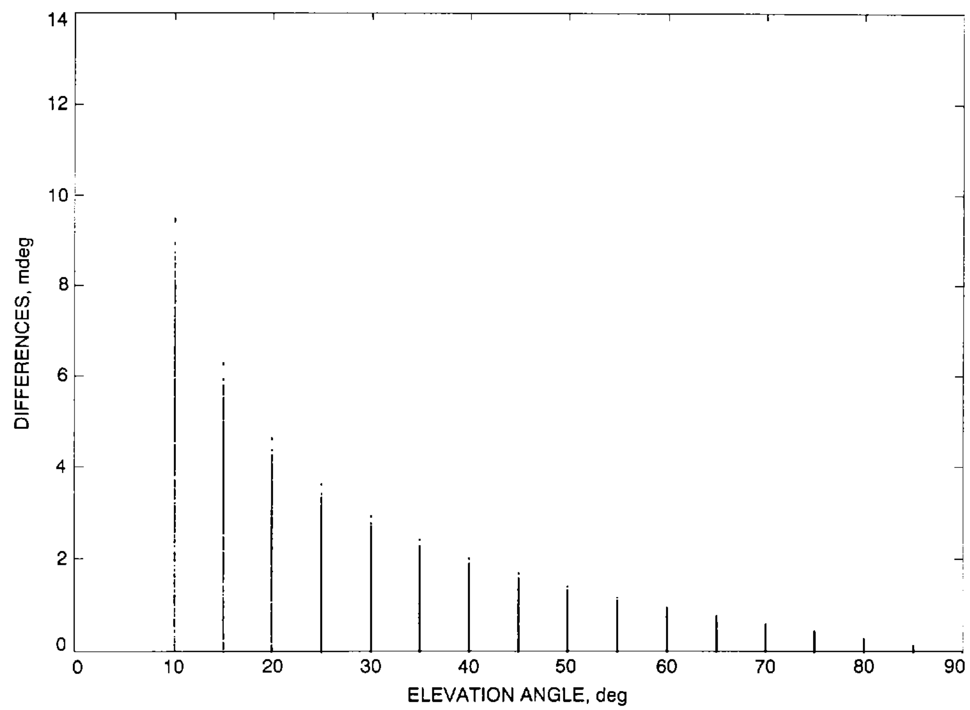

Fig. 4. Absolute difference between actual weather-based refraction corrections and default corrections for October 1990.

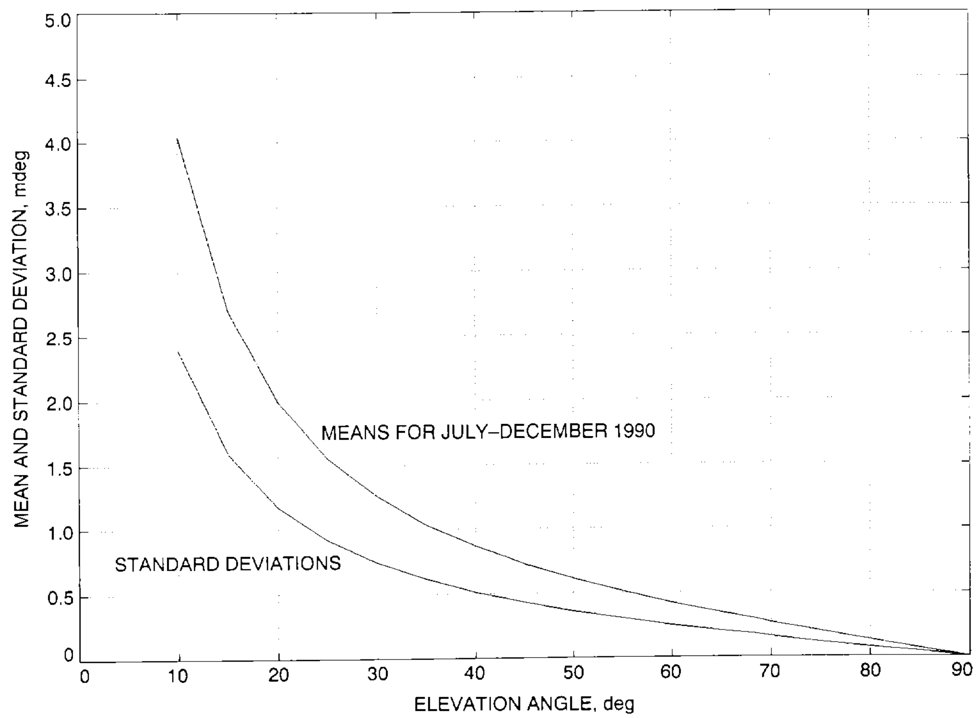

Fig. 5. Mean and standard deviation of the absolute difference between default and actual refraction corrections during July–December 1990.

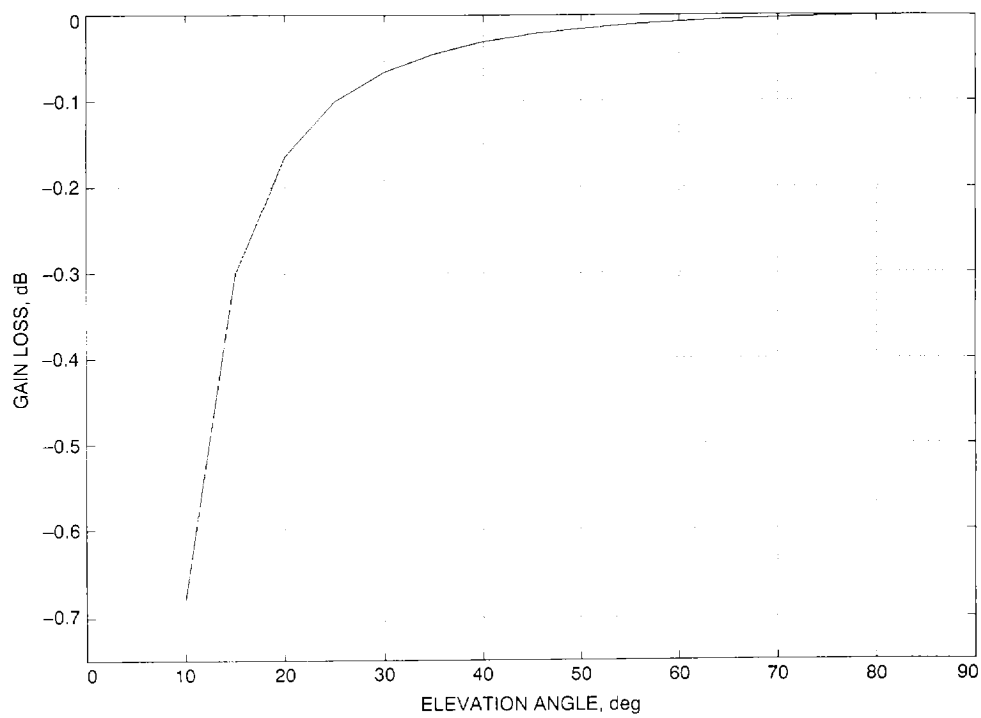

Fig. 6. Gain loss for refraction pointing error, July–December 1990.

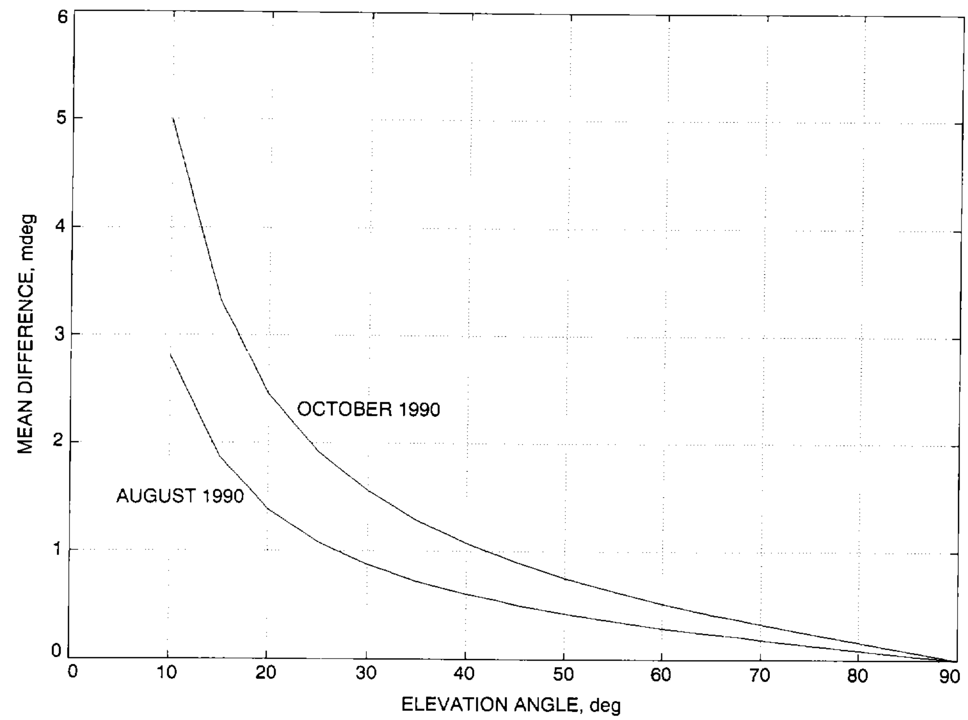

Fig. 7. Mean of the absolute difference between default and absolute refraction corrections, August and October 1990.

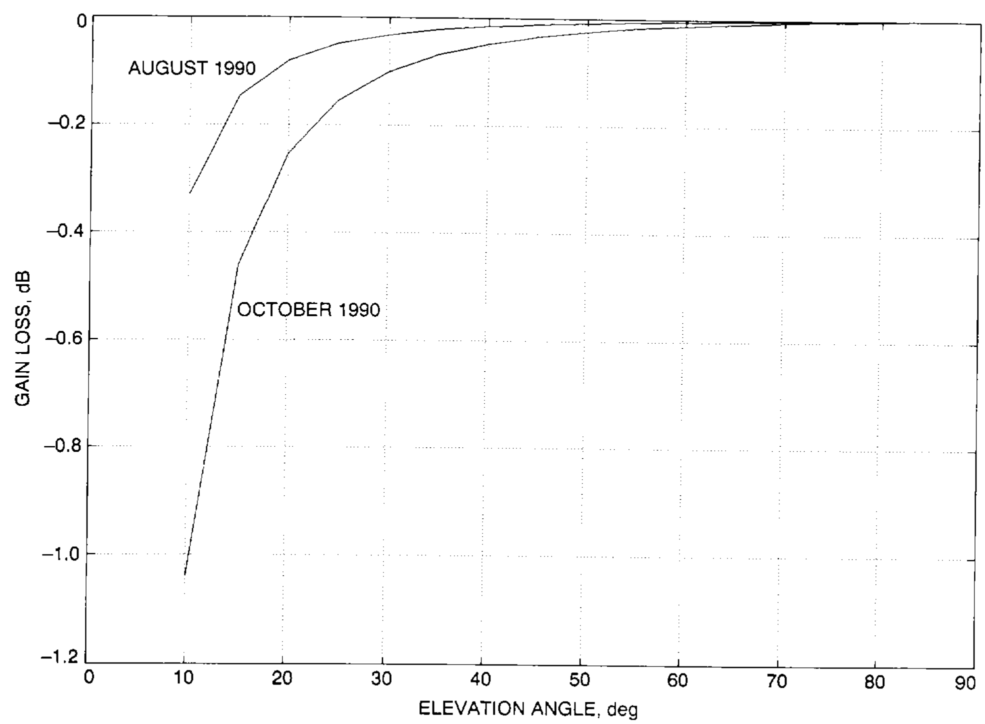

Fig. 8. Gain loss for refraction pointing error, August and October 1990.